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Article

Techno-economic analysis of a standalone hybrid energy system in Cambodia

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ABSTRACT

This study aims to present an economically feasible and environmental-friendly hybrid energy system that does not connect to the grid. In Cambodia, many rural areas are facing insufficient power supply problems and need more electricity supply. So, the designed system in this research can supply electric power to a community with 30 households in Krong Kracheh, Kratie Province, Cambodia. Three different designs of hybrid systems are considered. The first design is a hybrid system with PV modules, a diesel generator, and a battery. The second design is a hybrid system including a wind turbine, PV modules, diesel generator, and battery, and finally, a hybrid system that contains a wind turbine, diesel generator, and battery as the third design. According to the simulation results, the first configuration is the best design compared to the other two scenarios as it is the most cost-effective. The Present Net Cost, Cost of Energy, and system operating cost is 46,866 $, 0.268 $/kWh, and 2,327 $/yr, respectively. Besides, it has a total of 4,496.29 kg/yr pollutants emitted, which is less than the third configuration but more than the second configuration. The production of electricity for the first configuration is 23,820 kWh/yr, with a renewable fraction of 65.2%.

1. Introduction

Many developing countries, such as Cambodia, are working hard to provide electrification in rural areas nowadays. In Cambodia, over 85% of people live in rural areas [1]. However, the rural households with grid access are less than 9%, and they experience low power quality. Furthermore, some households also use rechargeable batteries and diesel generators to generate electricity by paying very high unit prices for it. The increase in fossil fuels consumptions to generate power will also increase pollution. In Cambodia, rural electrification is growing in many areas with the government-coordinated electrification program [2]. Basically, the program is to let local entrepreneurs sell electricity to the users in the existing market. However, electricity is still insufficient as demand exceeds supply. Figure 1 is a graph by International Energy Agency (IEA), showing the electricity consumption in Cambodia from 1995 to 2018. Electricity consumption has been increasing at a rate of 8.65% starting from 1990 [3]. To overcome the over-demand problem, some other appropriate solutions need to be found to provide electricity in rural areas. For instance, apply renewable resources for electricity generation purposes in rural areas. PV modules are used to generate electricity by absorbing solar energy and converting it into electricity. With the use of solar energy, electricity bills will be reduced, and maintenance costs will be relatively low. Cambodia has great potential in the solar energy field. The high value of solar irradiation can help the country to overcome the growing electricity demands problem. Wind turbines can also be used to produce electricity by converting wind energy into electrical energy. In the data of annual average wind speed obtained, the areas with 5 m/s wind speed have the potential to apply wind energy to generate electricity. Furthermore, a hybrid generation system that has a diesel generator can overcome the inconsistency of wind patterns problem [2]. In this study, a financially attainable and eco-friendly off-grid hybrid energy system will be presented to power a rural area with 30 households in Cambodia. Besides, there are three types of hybrid energy systems to be introduced and made comparison. The optimal system with lower cost is selected to apply in the rural area. Besides, sensitivity analysis is also implemented by the input of different key parameters such as project lifetime, nominal discount rate, fuel price, and so on. The organization of this

case study is as follows: Section 1 introduces the general knowledge and aim of the study. Section 2 reviews related previous articles written by different authors. Section 3 describes the methodology of this study. Section 4 introduces the modeling and system components of this study. Section 5 introduces and describes the meteorological data. Section 6 explains the load consumption of this study. Section 7 explains the system simulation of the study, and the analysis of the study, including economic analysis and sensitivity analysis, is explained in Section 8. Section 9 presents the results of simulation and optimization and the discussion about the optimal design. The conclusion is presented in Section 10, and Section 11 is the references.

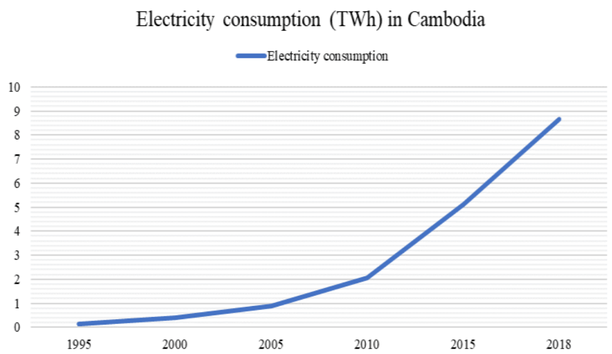

Figure 1. Electricity consumption in Cambodia from 1995 to 2018 [3]

Many communities around the world are trying to implement a hybrid energy system that does not connect to the grid because it can be more economically feasible and can reduce environmental pollution. The combinations of PV modules, diesel generator, LA battery, and Li-ion battery hybrid energy system in a remote village in Godagari, Rajshahi, Bangladesh, was presented in [4]. This hybrid power system with LA and Li-ion battery is also analyzed by using Load Following, Cycle Charging, and Combined Dispatch Strategies (CDS). Results showed that the system with combinations of PV modules, diesel generator, and LA battery using LF dispatch strategy has the lowest NPC, COE as well as operating cost. Thus, it is more economically feasible and has environmental benefits [5]. A hybrid energy system that contains PV modules, wind turbines, and a Biogas generator that implemented in Leopard Beach village in Hongsibao district, Ningxia province of China. The methodology described the input data, stimulation by HOMER, and economic and sensitivity analysis. The simulation results found that the system with a combination of PV modules, wind turbines, a Biogas generator, and the battery is the most economically feasible system as it has a low value of NPC and COE [6]. A hybrid power system with a combination of PV modules, a diesel generator, and a battery was applied in Harbin, China. This system is implemented to supply electricity to 140 households. The methodology described the system stimulation and the input parameters. According to the results, the system with a combination of PV modules, a diesel generator, and a Battery with an LF dispatch strategy was the best system as it is economically friendly [7]. A hybrid energy system with a combination of PV modules, wind turbines, diesel generators, and the battery has been implemented to supply electricity for 50 households in Shafar, Hajjah province, Yemen. The methodology of this study describes the system input parameters and system components. From the results obtained, the system with a combination of PV modules, wind turbines, diesel generator, and the battery has optimal reduction of CO_2 emissions and low system cost [8]. A case study of 3 housing regions in Jubail Industry city, Saudi Arabia. The hybrid energy system with PV modules, wind turbines, diesel generator, and battery, as well as the hybrid energy system with PV modules, wind turbines, and the battery has been considered. The methodology mentioned meteorological data and system components. Their research showed that systems with PV modules, wind turbines, and batteries have the least NPC, COE, and annualized cost. Thus, it was feasible to generate electricity in the residential. The electricity generation by hybrid energy system with PV modules, diesel generator, and battery were implemented in Fouay village, Benin [10]. The methodology mentioned site description, electrical demand assessment, resources assessment, and modeling of the hybrid energy system. The results presented that the system with PV modules, diesel generator, and battery was the optimal design as it came with the lowest NPC and was more environmental-friendly compared to the other cases [10]. Three types of hybrid energy systems used to supply electricity for residential and agricultural purposes in Yamunanagar district, Haryana, India, were compared. Results showed that the system with wind turbines, PV modules, and the battery has NPC of $228,353 and COE of 0.288 $/kWh. Hence, it was the optimal and most economical system [11]. A study case of the hybrid energy system with a combination of PV modules, wind turbines, Biomass generator, and battery applied in Korkadu, Union Territory of Pondicherry, India, to power the remote village. The load demand of the village was expected to be 179.32 kWh/day. The research showed that the system with a combination of PV modules, wind turbines, a Biomass generator, and a battery is the optimal design as it has the least cost configuration compared to the other cases.

The research considered a hybrid energy system with a combination of PV modules, wind turbines, diesel generators, and batteries as a power supply in Dongola, Sudan. Besides, an energy system with only a diesel generator was considered to make a comparison with this configuration. According to the results, the value of NPC and COE of the system with a combination of PV modules, wind turbines, diesel generators, and batteries was the lowest. Thus, it was the optimal design which was also economically feasible [12, 13]. A case study of the hybrid energy system with a combination of PV modules, wind turbines, and fuel cells applied in Çeşme district, Izmir province, Turkey. Two storage options, electrolyzer, and battery were used and compared in this study. The application of a hybrid energy system was to supply electricity to the residential. Results showed that a system with a combination of PV modules, wind turbines, and battery has optimal performance [14]. This research is a comparison of the hybrid energy system with PV modules and battery and hybrid system with PV modules, wind turbines, and battery for electrification purposes in the KhshU site in Khomeinishahr, Isfahan province, Iran. Results showed that a hybrid system with PV modules and battery has a lower value of NPC and COE. Therefore, it showed optimal performance and was economically feasible [15]. The hybrid energy system with wind turbines, PV modules, Biodiesel generator and battery, hybrid energy system with wind turbines, Biodiesel generator, and battery, as well as a hybrid energy system with PV modules, Biodiesel generator, and battery were applied in Fedeshk, South Khorasan, Iran to generate electricity. The results found that a system with PV modules, a Biodiesel

generator, and a battery is the most economical system. Based on [16], a hybrid energy system with PV modules, a diesel generator, and a battery generate electricity was implemented in Pulau Banggi and Tanjung Labian, Sabah, Malaysia. The purpose of the hybrid energy system was to generate electricity for the residents. From the results, a system with PV modules, a diesel generator, and a battery have optimal performance compared to a 100% renewable energy system. The total NPC and COE of the system were the lowest compared to the others [17]. A performance evaluation of a hybrid system that contains PV modules, wind turbines, diesel generator, and battery applied in Berjaya Tioman Resort, Tioman Island, Malaysia, was performed in this research. According to the outcomes, the system with a combination of PV modules, wind turbines, diesel generators, and batteries was more cost-effective and environmental-friendly compared to a diesel-only system. This is due to the reason that the total NPC and COE of the system were the lowest. Besides, the system has the highest percentage of renewable energy resources to be used.

Shahzad et al. [18] considered different configurations of PV/Biomass hybrid energy systems to supply electricity for the rural area in Layyah, Punjab province, Pakistan, for agricultural farm and residential community purposes. According to the results, the optimal system consisting of 10 kW PV modules, 8 kW biomass generator, 32 storage batteries, and 12 kW converter has the lowest value of total NPC and investment cost. The hybrid energy system with PV modules, diesel generator, and battery was considered in this research. The application of the hybrid energy system was to power a rural area in southern Algeria. Based on the outcomes of the research, the combination of 5 kW PV modules, 2.6 kW diesel generator, 24 batteries, and 4.5 kW converter configuration has the lowest total NPC. Thus, it was the optimal and most cost-effective hybrid energy system [19]. The research was carried out to power the rural areas in Colombia by applying a hybrid power system with PV modules, wind turbines, and diesel generators. Three rural areas that are selected are Uribia in La Guajira, Unguia in Choco state, and Jerico in Boyaca state. In this study, different scenarios were simulated and optimized for rural areas. The results showed that a system with PV modules, wind turbines, and a diesel generator is the most economically convenient for Uribia. For Unguia and Jerico, a system with PV modules and a diesel generator is the most economically convenient [20]. Salehin et al. [21] assessed the hybrid energy system with PV modules and diesel generator and hybrid energy system with wind turbines and diesel in Kutubdia Island, Bangladesh, which was carried out in this research. The methodology of the study described the assessment of energy resources, system components, system optimization, as well as analysis of the system. The results showed that a system with PV modules and a diesel generator has a shorter equity payback period coupled with the lowest COE [22]. A hybrid energy system with a combination of wind turbines, PV modules, diesel generator, and battery applied in KLIA Sepang Station, Selangor, Malaysia. The methodology mentioned the data resource analysis, location analysis, and system components. From the results, the value of COE and NPC of a hybrid energy system, which contains wind turbines, PV modules, a diesel generator, and a battery, is lower when compared with conventional electricity generation systems. A hybrid energy system with a combination of PV modules, wind turbines, diesel generators, and the battery was set up to power 150 households in Siyambalanduwa, Sri Lanka. From the results obtained, the hybrid energy system with 40 kW wind turbines, 30 kW PV modules, 222 kWh battery bank, and 25 kW diesel generator has optimal performance. The COE of the system is low [23]. Table 1 below shows the techno-economic analysis of some global and local hybrid systems.

2. Case study

2.1 Site description

Cambodia is a tropical country that has southeast and northeast monsoons. The average daily global horizontal irradiation (GHI) in Cambodia is 5 kWh/m^2. The average wind speed in most parts of Cambodia is below 3 m/s, and the overall wind conditions are not satisfactory. However, there are a few areas in Cambodia that have more than 5 m/s of wind speed [2]. Based on the data obtained, Cambodia is a country that is rich in solar energy resources and wind energy resources. Thus, it is suitable to apply a hybrid energy system in this area. In this study, a small town called Krong Kracheh in Kratié Province, Cambodia (12°29.4'N, 106°1.7'E) is considered. Krong Kracheh is located in eastern Cambodia and has a total area of 88.7 km^2 [8]. This small town lies on the Mekong Riverbanks and has a population of around 33000. According to NASA Prediction of Worldwide Energy Resource (POWER), all the meteorological data, including solar radiation, clearness index, average wind speed, and temperature, are obtained. The monthly solar radiation and clearness index data are shown in Figure 2. In Krong Kracheh, the annual average solar radiation is 5.31 kWh/m^2/day, and the average clearness index is 0.548. The monthly average wind speed data is shown in Figure 3, and 3.62m/s of annual average wind speed is observed. On the other hand, the monthly temperature data of Krong Kracheh is shown in Figure 4, and the annual average temperature is 27.73°C.

2.2 Load Consumption

In this research, a small community with 30 households and 5 family members for each household is considered. Simple load demands are considered, which include fans, lighting, and television [9]. Table 2 shows the estimated electrical loads of a household. The daily load profile of a small community with 30 households is shown in Figure 5. The peak load demand is 12 kW, which happens between 6 to 10 pm. Figure 6 shows the monthly load profile of the 30 households. There is no peak month of load demand as Cambodia is not a country with 4 seasons (winter, autumn, spring, and summer). The yearly load profile is shown in Figure 7. In addition, the typical electricity load consumed by the community is 37.5 kWh.

2.3 Modelling and System components

There are three types of hybrid energy system configurations considered in this study. The first configuration in Figure 8 contains PV modules, a diesel-based generator, an LA battery, and a converter. The second configuration in Figure 9 includes PV modules, a wind turbine, a diesel-based generator, an LA battery, and a converter. Finally, the third configuration in Figure 10 has a wind turbine, diesel generator, LA battery, and a converter. The information on the system components is shown in Table 3.

2.3.1 PV Modules

In this project, Peimar SG310MBF PV modules, a product of PEIMAR, are considered. The electrical characteristics of the PV modules are shown in Table 3 [24]. The maximum output of the PV modules is 310 watts. Besides, the PV modules have an efficiency of 19.05%.

Table 1. Techno-economic analysis of some global and local hybrid energy systems

No.	Location	Electricity Consumption (kWh/day)	Peak Demand (kW)	Hybrid Energy System - off grid	NPC ($)	COE ($)	Initial cost ($)	Reference
1	Godagari, Rajshahi, Bangladesh	350	74.34	PV/Diesel/LA battery	444,768	0.32	NA	[4]
2	Hongsibao district, Ningxia province, China	620	78.62	PV/Wind/Biogas/Battery	587,013	0.201	293,599	[5]
3	Harbin, China	NA	832	PV/Diesel/Battery	8,162,822	0.48	1,775,000	[6]
4	Shafar, Hajjah, Yemen	886	111	PV/Wind/Diesel/Battery	732,356	0.137	214,000	[7]
5	3 housing regions, Jubail Industry city, Saudi Arabia	11,160, 4865 and 3288	685, 463 and 270	PV/Wind/Battery	9,900,000, 5,600,000 and 3,900,000	0.183, 0.224 and 0.244	NA	[8]
6	Fouay village, Benin	679	51.7	PV/Diesel/Battery	555,492	0.207	332,369	[9]
7	Yamunanagar district, Haryana, India	151.65	30.5	Wind/PV/Battery	228,353	0.288	NA	[10]
8	Korkadu, Union Territory of Pondicherry, India	179.32	19.56	PV/Wind/Biomass/Battery	295,270	0.14	NA	[11]
9	Dongola, Sudan	1650 and 11,730	NA	PV/Wind/Diesel/Battery	24,160,000	0.387	17,236,000	[12]
10	Çeşme district, Izmir province, Turkey	165.59	23.31	PV/Wind/Battery	225,227	0.412	167,553	[13]
11	Khomeinishahr, Isfahan province, Iran	3	0.388	PV/Battery	8173	0.546	NA	[14]
12	Fedeshk, South Khorasan, Iran	94.7	NA	PV/Biodiesel/Battery	NA	NA	NA	[15]
13	Pulau Banggi and Tanjung Labian, Sabah, Malaysia	NA	360 and 240	PV/Diesel/Battery	9,345,510 and 5,571,168	0.302 and 0.3118	536,081 and 302,203	[16]
14	Berjaya Tioman Resort, Tioman Island, Malaysia	13,048	1185	PV/Wind/Diesel/Battery	17,155,200	0.279	NA	[17]
15	Layyah, Punjab province, Pakistan	168.37	17.08	PV/Biomass/Battery	61,042.55	0.075	35,971.50	[18]
16	South Algeria	24	2.4	PV/Diesel/Battery	54,852	NA	49,172	[19]
17	Colombia	379, 180 and 213	88, 38 and 41	PV/Wind/Diesel	836,210, 372,736 and 445,207	0.473, 0.444 and 0.448	521,078, 227,350 and 268,100	[20]
18	Kutubdia Island, Bangladesh	218	37	PV/Diesel	218,615	0.353	NA	[21]
19	KLIA Sepang Station, Selangor, Malaysia	33	3.9	Wind/PV/Diesel/Battery	288,194	1.877	NA	[22]
20	Siyambalanduwa, Sri Lanka	270	25	PV/Wind/Diesel/Battery	296,000	0.34	553,000	[23]

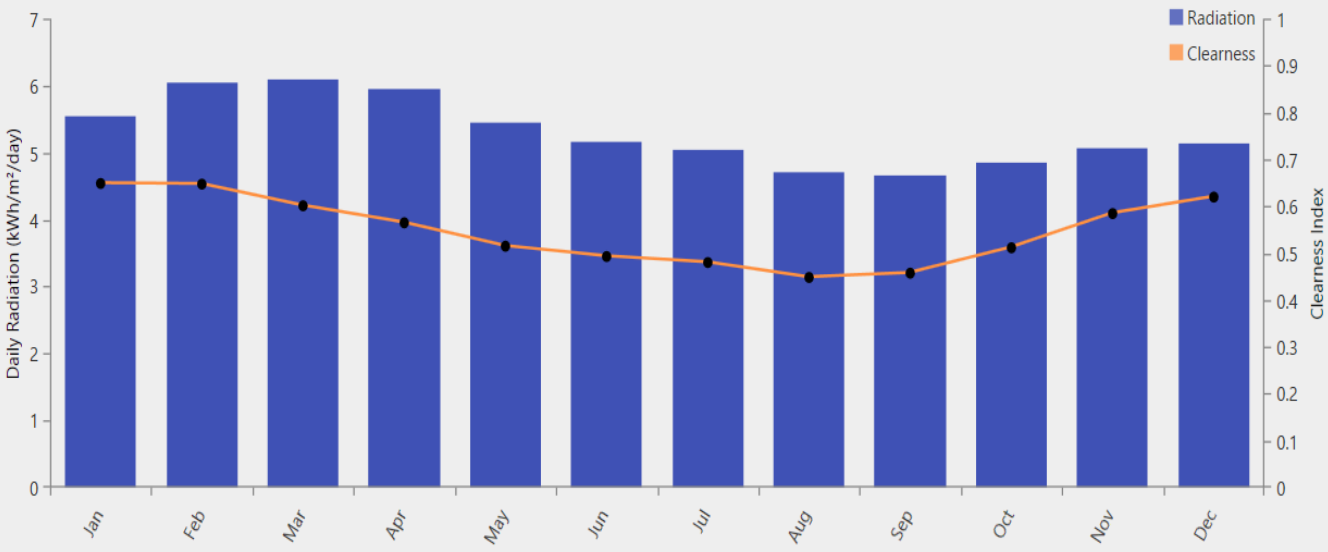

Figure 2. Monthly solar radiation and clearness index data

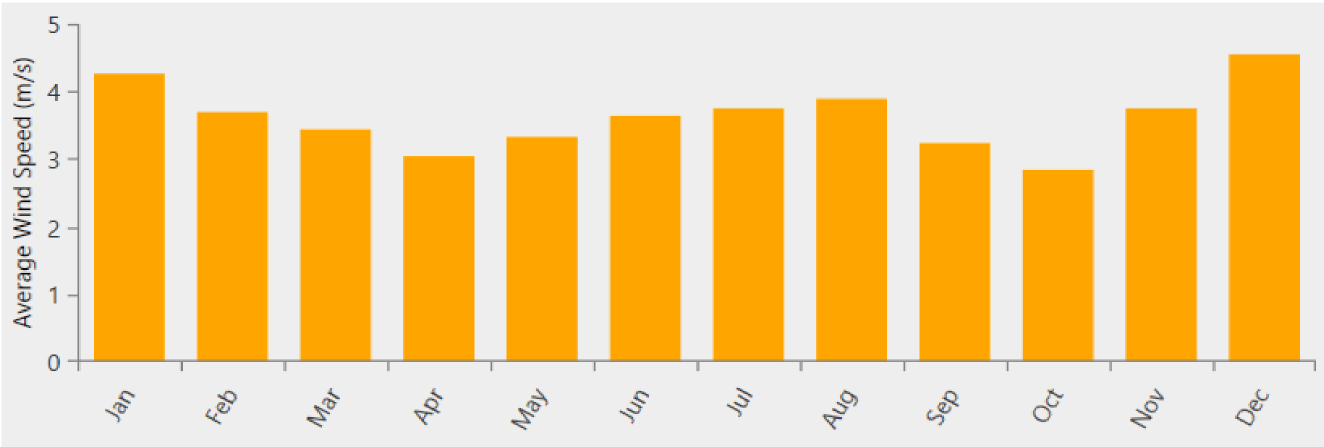

Figure 3. Monthly average wind speed in Krong Kracheh

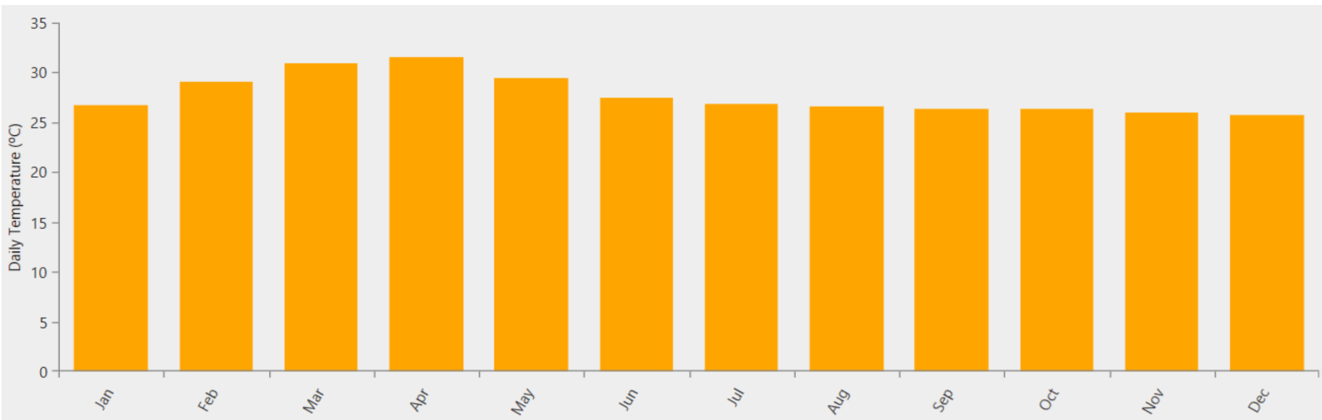

Figure 4. Monthly average temperature in Krong Kracheh

Table 2. Estimated electrical loads of a household

Load usage	Power consumption (W)	Used hours	Total consumption (kWh)
Fans	90	7	0.63
Lightning	50	6	0.3
Television	80	4	0.32
Daily consumtion of a househlold			1.25
Daily consumption of 30 households			37.5

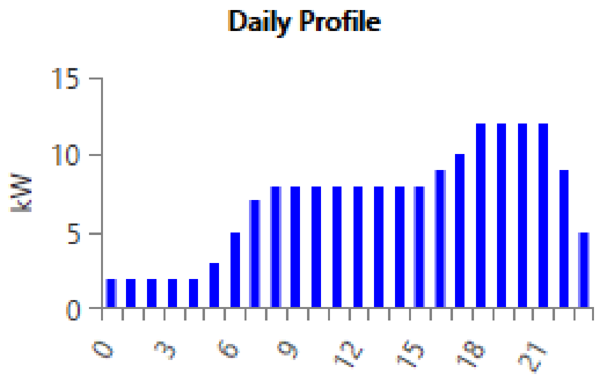

Figure 5. Daily load profile of a community with 30 households

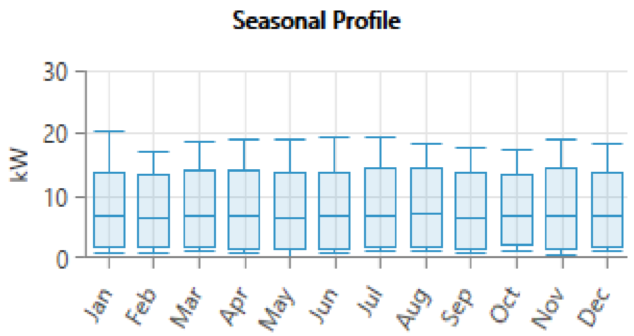

Figure 6. Monthly load profile of 30 households

The temperature coefficient of nominal power output is -0.37%/°C. 80% of the derating factor for PV modules is considered. The PV modules have a total lifetime of 30 years. Besides, \$650/kW of capital cost and \$650/kW of the replacement cost of the PV modules. The PV modules do not cost any O&M during the whole project lifetime (25 years).

2.3.2 Wind Turbine

In this study, Gaia-Wind 133-11kW wind turbine manufactured by Gaia-Wind is selected. This is a 3-phase wind turbine with a rated capacity of 11kW. The wind turbine can be generated with 400V of nominal voltage at a frequency of 50Hz. The wind turbine has a hub height of 18m and 25 years of a lifetime [25]. Besides, the wind turbine has \$55000 in capital cost, \$25000 in replacement cost, and \$850/year of O&M cost.

2.3.3 Diesel Generator

An auto-sized diesel generator is considered in this study. This generator will automatically change its size to meet the load. The smallest capacity will be produced by this generator to avoid capacity shortage. The fuel curve can be adjusted by the generator so that the size matches. The calculation of the diesel generator efficiency is shown below [26]. This generator has 43.2 MJ/kg of lower heating value and a 25% of minimum load ratio of rated capacity.

$$\eta_{gen} = \frac{3600 \; x \; P_{gen}}{\rho_{fuel} \; x \; F_c \; x \; LHV_{fuel}} \qquad \textbf{(1)}$$

Where:

$$P_{gen} = \; electrical \; output \; (kW)$$

$$\rho_{fuel} = \; fuel \; density \; (kg/m^3)$$

$$F_c = fuel \; consumption \; (l/h)$$

$$LHV_{fuel} = \; lower \; heating \; value \; of \; the \; fuel \; (MJ/kg)$$

The capital and replacement cost of this diesel generator is \$500, respectively. Besides, \$0.03/op.hour of O&M cost for the generator. In addition, the total lifetime of 15,000 hours is considered for the diesel generator.

2.3.4 Battery

The purpose of including a battery in the hybrid energy system is to store energy. The extra energy generated by the renewable sources plus the diesel generator will be stored in the battery until 100% state of charge. This study discovered 2VRE-1600TG Lead Acid battery is chosen as the battery bank. The rated capacity of the battery is 834 Ah at a voltage of 2.05V [27]. The performance characteristics of this battery are shown in Table 4. This battery has a 20% minimum state of charge so that it can avoid damaging the storage bank. This battery has \$425.21 of capital cost and \$425.21 of replacement cost but no O&M cost charge. Besides, this battery has a total lifetime of 20 years.

2.3.5 Converter

The bi-directional system converter is connected between AC and DC buses. The efficiency of the system converter is 95%. The system converter has a \$300 cost for the replacement and a \$300 capital cost. The system converter does not cost any O&M. The system converter has 15 years of lifetime. Table 5 below shows the technical description of the components.

3. Methodology

In this research, three types of hybrid energy systems are studied as the conceptual design of the hybrid energy system that does not connect to the grid. All the hybrid energy systems designs are shown in Figure 7, Figure 8, and Figure 9, respectively. The AC bus is connected by a diesel generator, wind turbine, PV modules, and load demand, while the DC bus is connected by a battery bank. Both AC and DC bus exchange power using a converter that is bi-directional. When the power supplied to the users is enough, the battery storage will store the remainder energy from the wind turbine, PV modules, and diesel generator. Besides, the simulation of energy systems is done by the HOMER Pro software tool.

3.1 System simulation and optimization

The system simulation process can identify the optimal size or usage of each system component. HOMER calculates the energy balance of the operation of the hybrid energy system at each time step of the year.

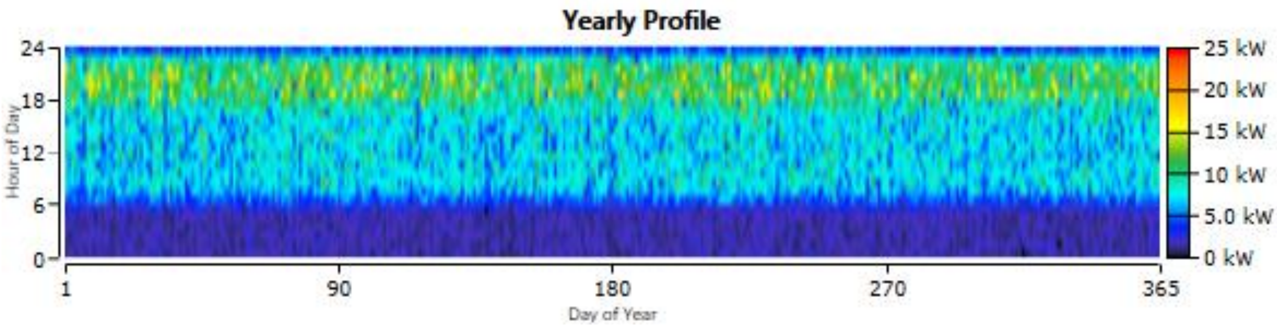

Figure 7. Yearly load profile of 30 households

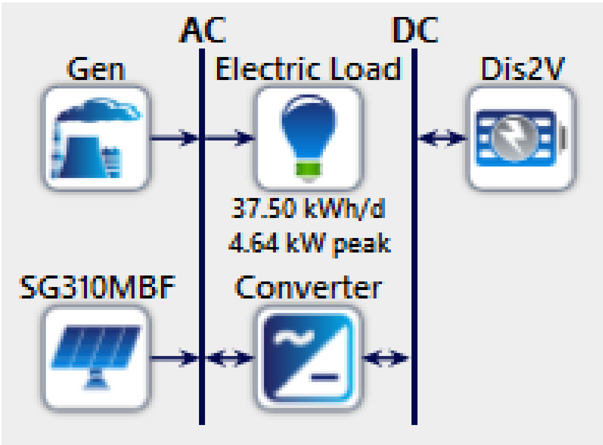

Figure 8. Schematic of hybrid system with PV modules, turbine, diesel generator, and battery

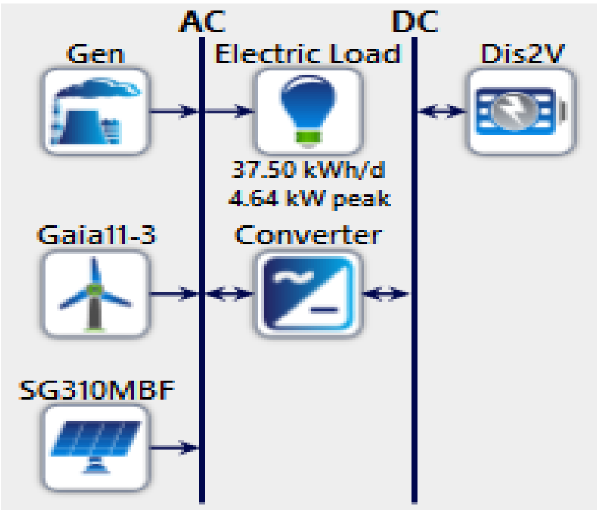

Figure 9. Schematic of hybrid system with a wind PV modules, diesel generator, and battery

In addition, the electric and thermal demand in that time step is compared with the energy which can be provided by the system in that time step. Other than, when discussing the systems, which consist of fuel-powered generators or batteries, the generator operation strategy, as well as the choice to charge or discharge the batteries, can be chosen by HOMER in each time step [28]. Furthermore, every calculation for the energy balance, which is considered a hybrid energy system, is performed by HOMER. At that point, HOMER will decide on the possibility of a design.

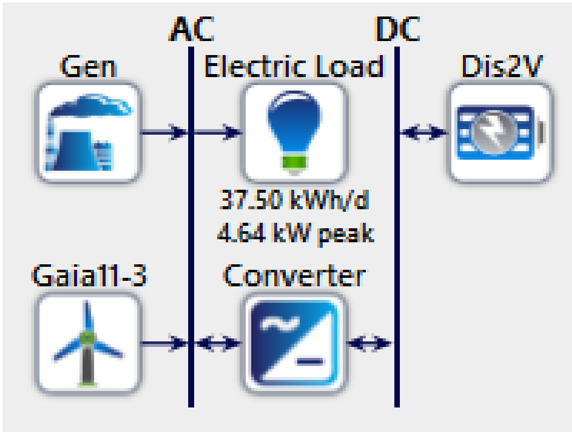

Figure 10. Schematic of hybrid system with wind turbine, diesel generator, and battery

Table 3. Electrical characteristics of PV modules [24]

Electrical characteristics	**Output values**
Nominal output (Pmax)	310W
The voltage at Pmax (Vmp)	33.45V
Current at Pmax (Imp)	9.27A
Open circuit voltage (Voc)	1500V
Short circuit current (Isc)	15A
Module efficiency	19.05%

The installation and system operating cost over the lifetime of the project will be assessed by HOMER as well. The costs that are accounted for in the system cost calculations are capital, replacement, operation and maintenance, fuel, and interest costs [28]. After all, simulations then come to the optimization step. In the optimization process, HOMER aims to minimize the NPC of every system. Then, all the feasible systems are sorted by minimum NPC for comparison purposes.

Table 4. Performance characteristics of LA battery [27]

Performance characteristics	Output value
Nominal voltage	2.05V
Nominal capacity	1.67kWh
Maximum capacity	834Ah
Capacity ratio	0.569
Roundtrip efficiency	80%
Maximum charge current	170A
Maximum discharge current	770A

3.2 Economic analysis

The economic analysis of the hybrid energy system includes the Cost of Energy (COE) and Net Present Cost (NPC). Besides, the electricity production of each operating component is analyzed as well. HOMER will decide the optimal solutions according to the lower NPC and COE. HOMER defines COE as the sum of a system's cost over the total energy generated in one year. To calculate the COE, the annualized capital cost, replacement cost, as well as operation & maintenance cost are summed up and then divided by the total energy generated in one year.

$$COE = \frac{C_c + C_r + C_{o\&m}}{E_t} \tag{2}$$

Where:
C_c = annualised capital cost ($/yr)
C_r = annualised replacement cost ($/yr)
$C_{o\&m}$ = annualised operation & maintenance cost ($/yr)
E_t = total energy generated in one year (kWh/yr)

On the other hand, NPC is the total cost spent on the hybrid energy system during the whole project's lifetime. To calculate NPC, the annualized capital cost, replacement cost, and operation & maintenance cost need to be summed up and then divided by the capital recovery factor.

$$NPC = \frac{C_c + C_r + C_{o\&m}}{CRF(i,N)} \tag{3}$$

The capital recovery factor is a ratio that can be utilized to calculate the present value of an annuity [29].

$$CRF(i,N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{4}$$

Where:
$CRF = capital\ recovery\ factor$
$i = real\ discount\ rate$
$N = number\ of\ years$

The formula to calculate the real discount rate is shown below [30].

$$i = \frac{i' - f}{1+f} \tag{5}$$

Where:
$i' = nominal\ discount\ rate\ (6\%\ in\ this\ project)$
$f = expected\ inflation\ rate$

3.3 Sensitivity analysis

Sensitivity analysis is performed by entering multiple values for a specific input variable. With these values, the sensitivity of the outputs can be determined. The analysis process is repeated with different values entered for the sensitivity variables to get the optimal result. The sensitivity variables include average wind speed, fuel cost, interest rate, etc. Besides, sensitivity analysis of a study case can be a reference to the other case study. In other words, this can provide a sample to other hybrid energy system installations with similar conditions [31].

4. Results and discussions

In this study, 24,391 solutions were simulated by the HOMER Pro software tool. The simulation and optimization results of various hybrid energy systems are presented in this section. In addition, the results of the sensitivity analysis and the comparative analysis of the optimal system are also highlighted.

4.1 System simulation results

There is 37.5 kWh/day of load demand in this study for the project lifetime of 25 years, 6% of the nominal discount rate, 0.638 $/liter of diesel fuel price, 5.31 kWh/m^2/day of annual average solar radiation, and 3.62 m/s of annual average wind speed were the initial stimulation conditions.

Table 5. Technical description, cost, and lifetime of the system components

Components	Technical description	Capital cost ($)	Replacement cost ($)		O & M ($)	Lifetime (yr)
PV modules	310W	650	650		0	30
Wind Turbine	11kW	55,000	25,000		850/yr	25
Diesel Generator	5.2kW (in this project)	500	500		0.03/op.hour	15000hrs
LA battery	2.05V, 834Ah (1.67kWh)	425.21	425.21		0	20
System converter	1kW	300	300		0	15
Nominal discount rate	6%					
Fuel price	0.638 $/liter					

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The three optimal sizing configurations considered in this study are analyzed in detail. And the three optimal sizing configurations are hybrid energy systems with PV modules, diesel generators, and battery, hybrid energy systems with wind turbines, PV modules, diesel generators, and battery, and hybrid energy systems with wind turbines, diesel generators, and battery. In the first configuration of the hybrid energy system, the electricity is generated by the PV modules and diesel generator. The total net present value, levelized cost of energy, and operating cost for this configuration are $46,866, $0.682, and $2,327, respectively. Figure 11 shows the Summarised Net Present Cost, and Figure 12 shows the cash flow of the system throughout the project's lifetime. The autosize genset (generator) is the most expensive part of the system, while the system converter is the cheapest part, as shown in Figure 8. In Figure 12, there is $17,120.63 of capital cost at the beginning of the project. There will be extra expenses, which is replacement cost in the 7th, 8th, 13th, 15th, 16th, 19th, 24th, and 25th year. Besides, in the 25th year, there is $9,098.29 of salvage in this configuration. The production of electricity for this configuration is 23,820 kWh/yr. The renewable fraction of this configuration is 65.2%. Figure 13 shows the monthly electricity generated by the hybrid system. Besides, Table 6 shows the pollutants emitted by the system. There are 4,430 kg/yr of CO_2, 27.9 kg/yr of CO, 1.22 kg/yr of UHC, 0.169 kg/yr of PM, 10.8 kg/yr of SO_2, and 26.2 kg/yr of NO emitted by the system.

In the second configuration of the hybrid energy system, wind turbines, PV modules, and diesel generators are used to generate electricity. From the simulation, the total NPC, levelized COE, and operating cost of the hybrid energy system is obtained. It was found that the NPC of this system is $102,052, the COE is $0.583, and the operating cost is $2,550. Figure 14 is the Net Present Cost summary, and it shows that the Gaia-Wind 11kW 133 3-phase (wind turbine) is the most costly part of the system, while the system converter is the cheapest part. In Figure 15, the cash flow of the system in 25 years is shown. In the graph, it is shown that the capital cost is the majority of expenses in the project's lifetime. Besides, there are replacement costs that need to be expended in the 7th year, 13th year, and 19th year. In addition, there is $3508.05 of salvage in the 25th year. The total electricity production of this configuration is 27,934 kWh/yr, and 76% of the renewable fraction for this system. The monthly electricity production of this configuration is shown in Figure 16. Besides, the pollutants emitted by the system are simulated and shown in Table 7. There are 3,116 kg/yr of CO_2, 19.6 kg/yr of CO, 0.857 kg/yr of UHC, 0.119 kg/yr of PM, 7.63 kg/yr of SO_2, and 18.5 kg/yr of NO emitted by the system. In the third configuration of the hybrid energy system, the electricity is generated by the wind turbine and diesel generator. In this configuration, the total NPC is $120,678, and the Levelized COE is $0.690, while the operating cost is $4,585.

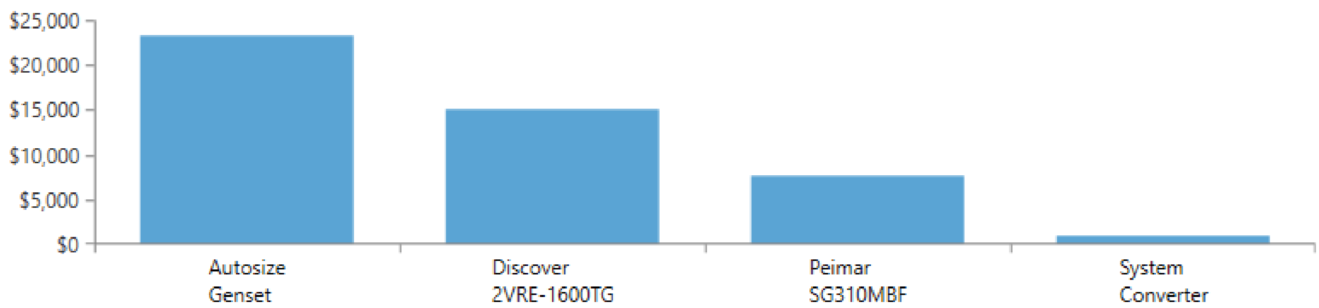

Figure 11. The summarized net present cost of the PV/Diesel/battery hybrid energy system

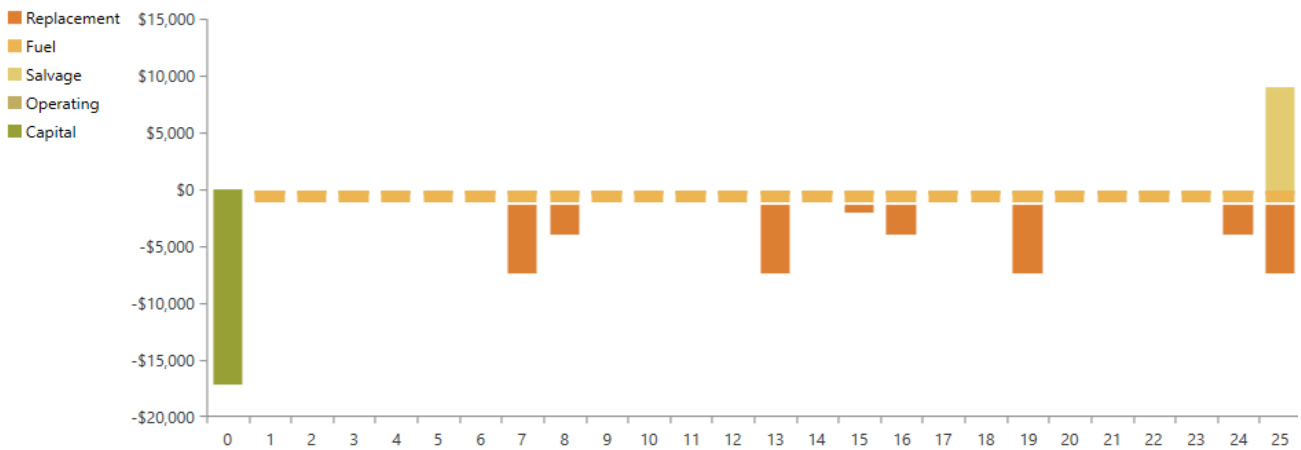

Figure 12. Cash flow of the PV/Diesel/battery hybrid energy system throughout the project's lifetime

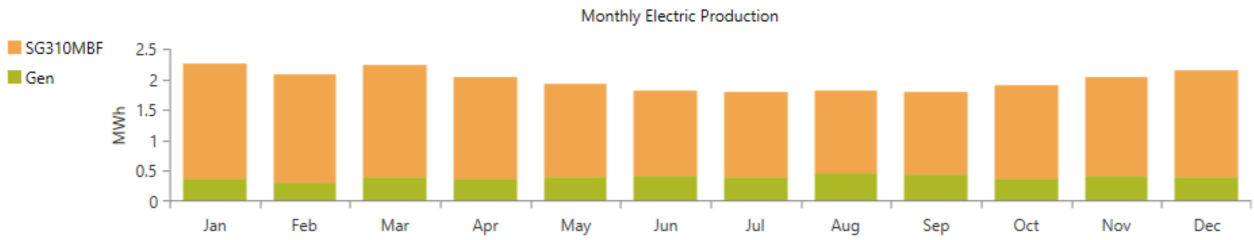

Figure 13. Monthly electricity produced by the PV/Diesel/battery hybrid energy system

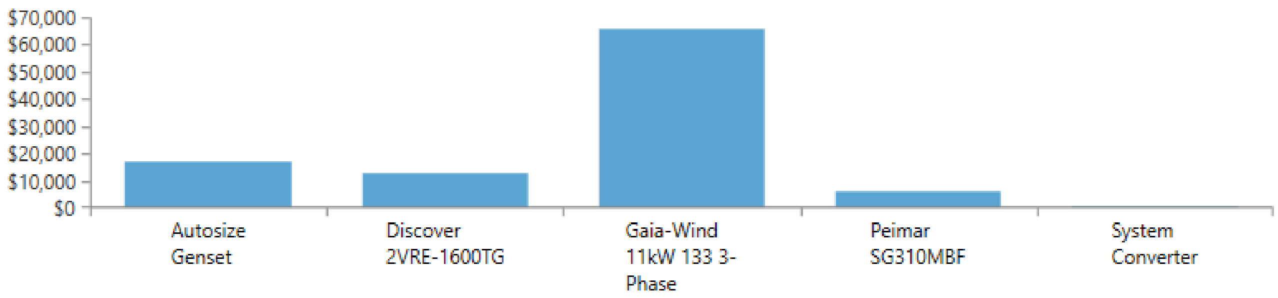

Figure 14. Summarised net present cost of the Wind/PV/Diesel/battery hybrid energy system

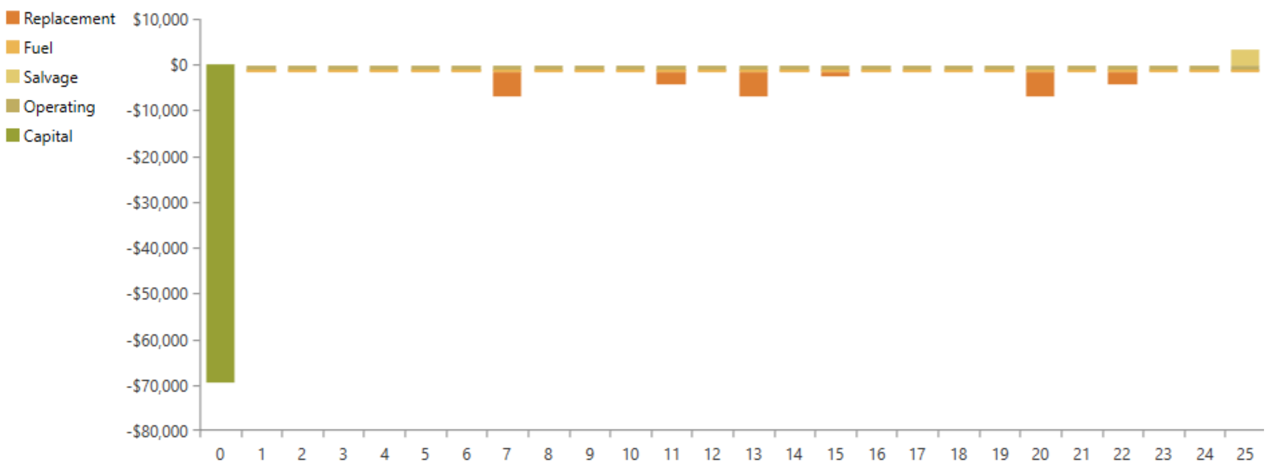

Figure 15. Cash flow of the Wind/PV/Diesel/battery hybrid energy system throughout the project lifetime

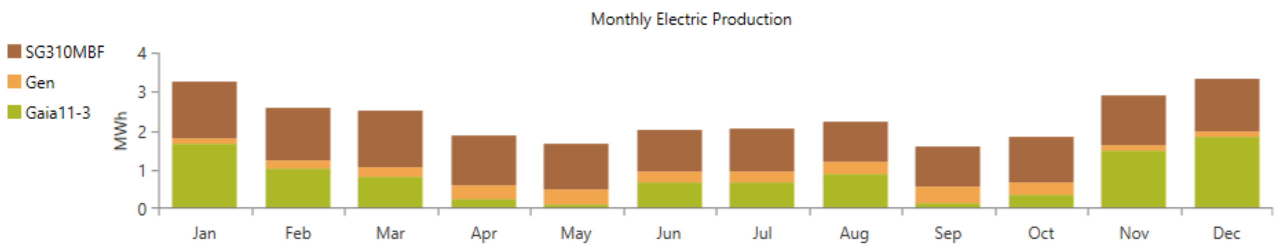

Figure 16. Monthly electricity produced by the Wind/PV/Diesel/battery hybrid energy system

Table 6. Pollutants emitted by the PV/Diesel/battery hybrid energy system (first configuration)

Quantity	Value (kg/yr)
Carbon Dioxide (CO^2)	4,430
Carbon Monoxide (CO)	27.9
Unburned Hydrocarbons (UHC)	1.22
Particulate Matter (PM)	0.169
Sulfur Dioxide (SO^2)	10.8
Nitrogen Oxides (NO)	26.2

Table 7. Pollutants emitted by the Wind/PV/Diesel/battery hybrid energy system (second configuration)

Quantity	Value (kg/yr)
Carbon Dioxide (CO_2)	3,116
Carbon Monoxide (CO)	19.6
Unburned Hydrocarbons (UHC)	0.857
Particulate Matter (PM)	0.119
Sulfur Dioxide (SO_2)	7.63
Nitrogen Oxides (NO)	18.5

Figure 17 shows the summarized Net Present Cost of the system. The Gaia-Wind 11kW 133 3-phase (wind turbine) costs $65,865.85, which is the most expensive component in the system, while the cheapest component is the converter system, which costs $849.81. The system's cash flow in 25 years is shown in Figure 18. There is $62,061.87 of capital cost at the beginning of the project, which costs the most in the whole project. There are also replacement costs that need to pay in the 6th, 9th,11th, 15th, 16th, 17th, 21st, and 25th year. In addition, there is $3,530.84 of salvage in the 25th year. The total electricity production of this configuration is 19,121 kWh/yr and 33.1% of renewable fraction for this system. The monthly electric production of the hybrid energy system showed in Figure 19. Moreover, the emissions data of the system are tabulated and shown in Table 8. There are 8,301 kg/yr of CO_2, 52.3 kg/yr of CO, 2.28 kg/yr of UHC, 0.317 kg/yr of PM, 20.3 kg/yr of SO_2, and 49.2 kg/yr of NO emitted by the system.

4.2 System Optimization Results

The simulation results in it are referred to as the first configuration, second configuration, and third configuration of the hybrid system to achieve the community load demand. The comparative analysis is carried out to discover the system which is the most appropriate and optimal to be used. The summarised optimization results of three configurations, including the architecture, cost, and system, are shown in Table 9. According to Table 9, the cost of NPC and COE of the first configuration of the hybrid energy system is $46,866 and $0.268, respectively, which is the lowest compared to the other two systems. The second configuration of the hybrid energy system has a net present cost of $102,052 as well as a $0.583 cost of energy which is lower than the third configuration of the hybrid energy system but higher than the first configuration of the hybrid energy system. Yet, the third configuration of the hybrid energy system has the highest cost NPC and COE, which is $120,678 and $0.632, respectively. All three systems use the same dispatch strategy, which is Load Following. In addition, based in Table 9, the second configuration of the hybrid energy system has the highest renewable fraction (76%) and the least diesel fuel consumed (1,190 liter/yr). The renewable fraction of the first configuration of the hybrid energy system is 65.2%, which is higher than the third configuration of the hybrid energy system, but lower than the second configuration of the hybrid energy system, as well as the fuel consumption is 1,692 liter/yr, which is lower than the third configuration of hybrid energy system but higher than the second configuration of the hybrid energy system. The third configuration of the hybrid energy system has the lowest renewable fraction (33.1%) and highest fuel consumption (3,171 liter/yr) compared to the other two hybrid energy systems. Based on the emissions data above, the second configuration of the hybrid energy system emitted the least pollutants. The pollutants emitted total 3,162.71 kg/yr. The first configuration of the hybrid energy system emitted total pollutants of 4,496.29 kg/yr, which is less than the third configuration of the hybrid energy system but more than the second configuration of the hybrid energy system. The third configuration of the hybrid energy system emitted the highest number of pollutants, which had a total value of 8,425.40 kg/yr.

Based on the optimization results, the most cost-effective and optimal hybrid energy system that applies to 30 households in a small community in Krong Kracheh is the first configuration of a hybrid energy system that contains PV modules, diesel generators, and batteries. This system has the least amount in NPC, COE, and operating costs. Besides, the emissions of pollutants are acceptable as it is less than the base case in the study. Figure 20 is a graph that shows how the hybrid energy system saves money over the project's lifetime. The base case considered in this project is the configuration with only a diesel generator to produce electricity. Furthermore, this hybrid energy system is able to produce 23,820 kWh/yr of electricity load, which is sufficient for the small community. Figure 21 shows the daily operation in a day of July. The PV modules produced the most electricity at 10 am as the sunlight was the strongest during that time. Figure 22 shows the total electrical load served monthly averages. Note that the daily average maximum electrical load served every month is above 3 kW.

Table 8. Pollutants emitted by the Wind/Diesel/battery hybrid energy system (third configuration)

Quantity	Value (kg/yr)
Carbon Dioxide (CO_2)	8,301
Carbon Monoxide (CO)	52.3
Unburned Hydrocarbons (UHC)	2.28
Particulate Matter (PM)	0.317
Sulfur Dioxide (SO_2)	20.3
Nitrogen Oxides (NO)	49.2

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Table 9. Summarised optimization of three hybrid energy systems

Architecture	Configurations	PV/Diesel/battery	Wind/PV/Diesel/battery	Wind/Diesel/battery
	PV (kW)	12.1	6.76	-
	Wind turbine (11 kW)	-	1	1
	Generator (kW)	5.20	5.20	5.20
	LA battery	14	12	14
	Converter (kW)	2.21	2.31	1.75
	Dispatch strategy	LF	LF	LF
Cost	NPC ($)	46,866	102,052	120,678
	COE ($)	0.268	0.583	0.632
	Operating cost ($/yr)	2,327	2,550	4,585
	Initial capital cost ($)	17,120	67,789	62,061
System	Renewable fraction (%)	65.2	76	33.1
	Total fuel (liter/yr)	1,692	1,190	3,171

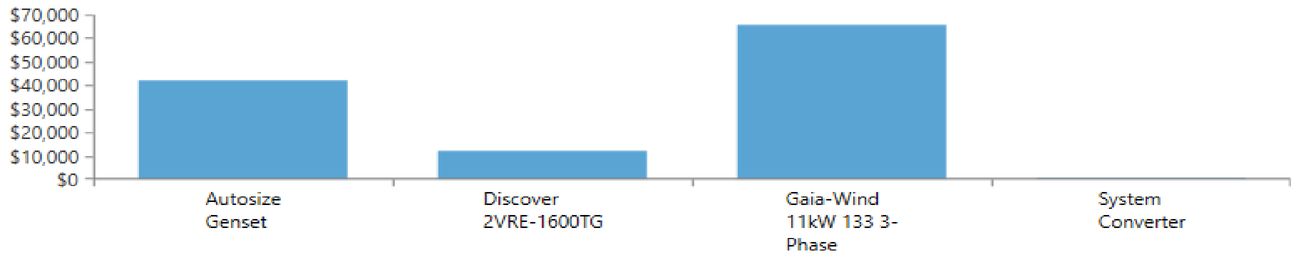

Figure 17. Summarised net present cost of the Wind/Diesel/battery hybrid energy system

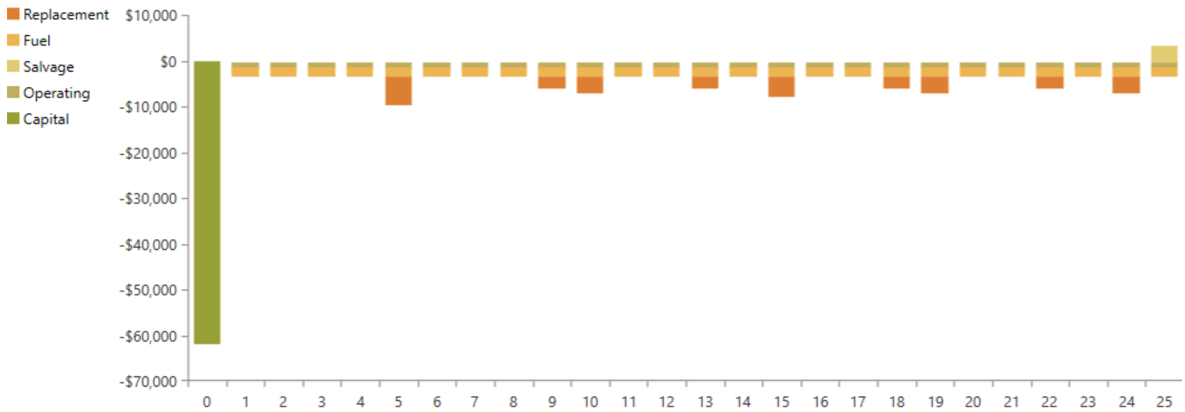

Figure 18. Cash flow of the Wind/Diesel/battery hybrid energy system throughout the project lifetime

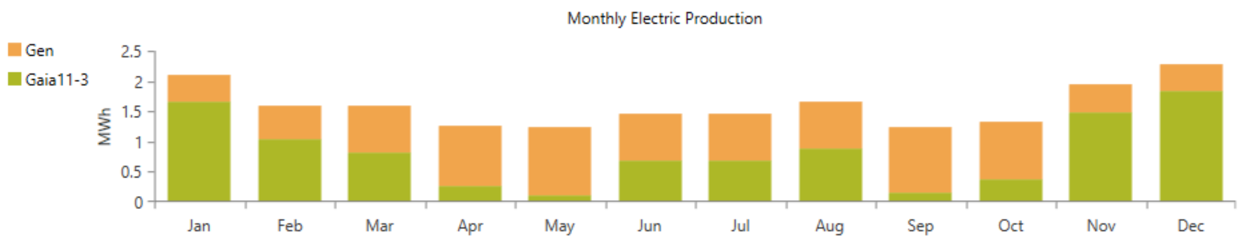

Figure 19. Monthly electricity produced by the Wind/Diesel/battery hybrid energy system

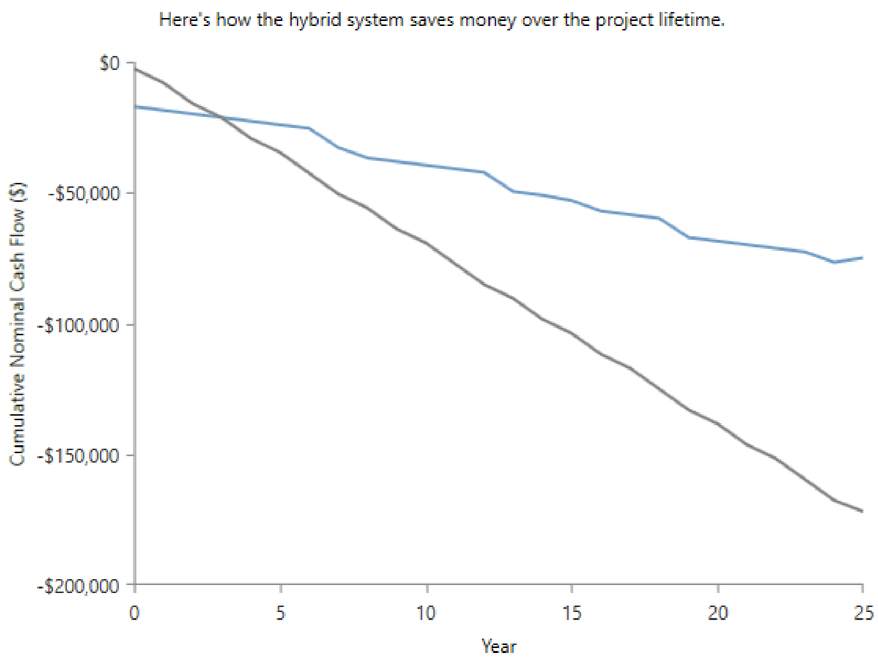

Figure 20. Graph of money savings by PV/Diesel/battery hybrid energy system over the project lifetime

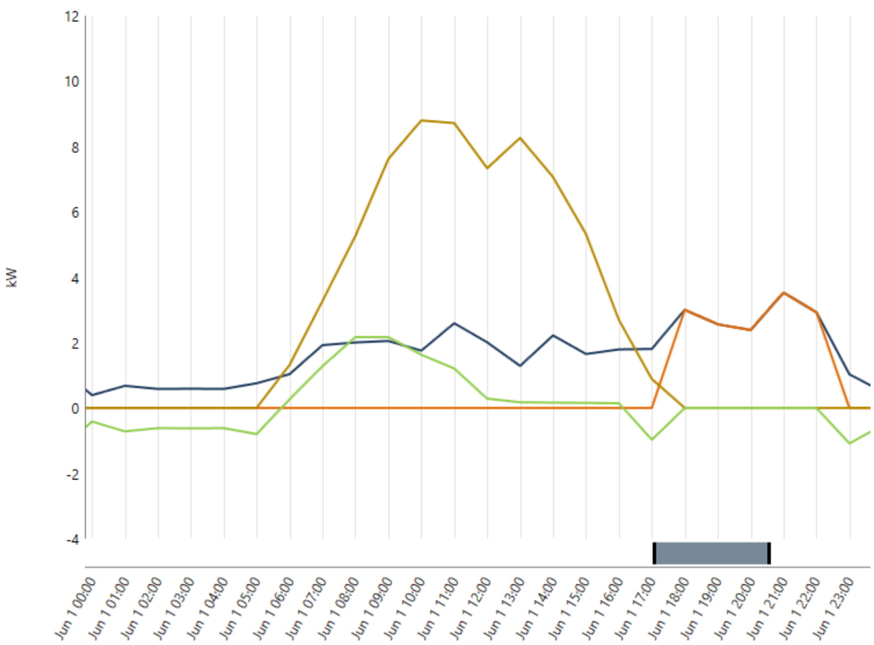

Figure 21. Daily operation of a day in June

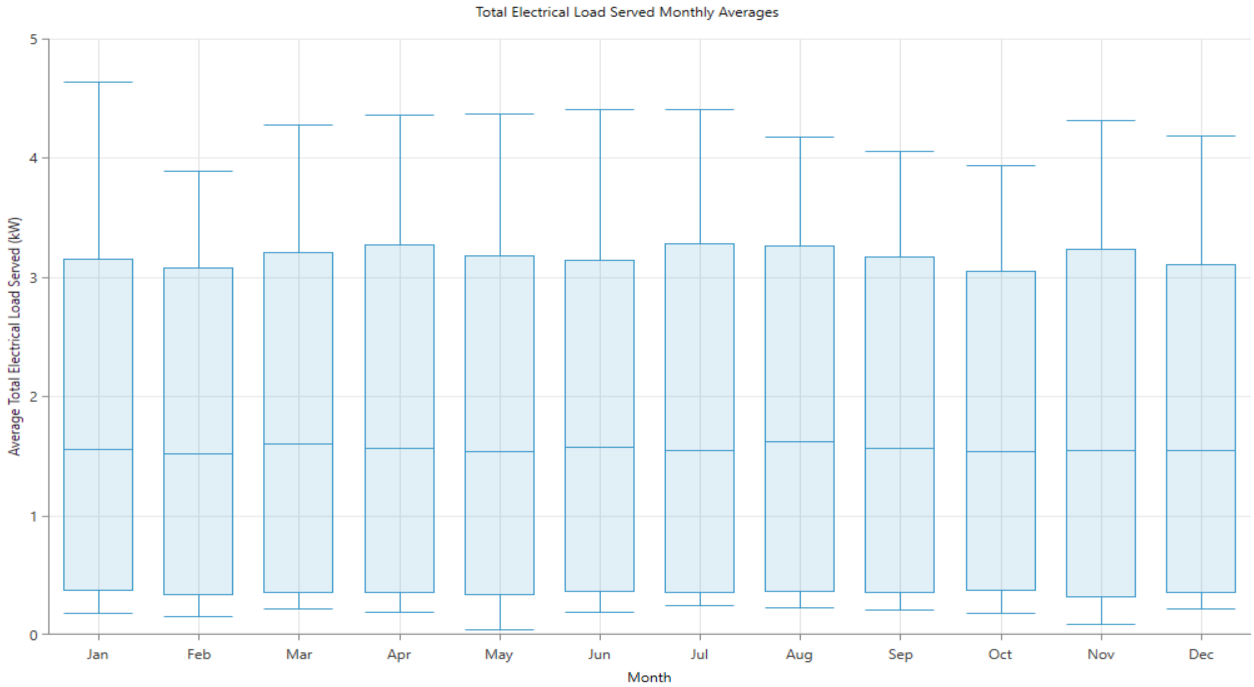

Figure 22. Total electrical load served monthly averages

5. Conclusion

The objective of this work is to present an economically feasible as well as environment-friendly hybrid energy system that does not connect to the grid to power a typical rural area in Krong Kracheh, Kratie Province, Cambodia. Besides, this hybrid energy system needs to generate electricity to power the small community built up of 30 households. Based on the simulation and optimization results, the most cost-efficient and optimal hybrid system is the first configuration of a hybrid energy system, which contains PV modules, diesel generators, and a battery. The components included in this hybrid energy system are 12.1 kW PV modules, a 5.2 kW diesel generator, 14 Lead Acid batteries as storage banks, and a 2.21 kW converter. This hybrid energy system can generate 23,820 kWh/yr of electricity load for the small community. Besides, the $46,866 of NPC, $0.268 of COE as well as $2,327/yr of operating cost of this hybrid energy system are the lowest. These results showed that the first configuration of the hybrid energy system is more economically friendly compared to the other 2 configurations of hybrid energy systems. Considering Cambodia is a tropical country, solar resources are usually abundant. Thus, the hybrid system of solar based will be suitable for supplying electricity in rural areas. Besides, the benefits of environmental-friendly will be achieved by using renewable energy. Therefore, the Cambodian government plays an important role in popularizing the application of hybrid energy system projects for electrification in rural areas. In addition, due to the high cost of the system, which may be unaffordable for the residents in rural areas, the Cambodian government can cooperate with the respective companies or provide financial aid in the application of hybrid energy system projects. Thus, this kind of project can run smoothly without financial problems, and the rural areas can enjoy electricity without connecting to the grids.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Conflict of interest

The authors declare no potential conflict of interest.

References

[1] Wimalaratna, Y. P., Hassan, A., Afrouzi, H. N., Mehranzamir, K., Ahmed, J., Siddique, B. M., & Liew, S. C. Comprehensive review on the feasibility of developing wave energy as a renewable energy resource in Australia. Cleaner Energy Systems, 100021, 2022.

[2] Cheng, B. W. Z., Mehranzamir, K., Afrouzi, H. N., & Hassan, A. Feasibility analysis and economic viability of standalone hybrid Systems for Marudi Electrification in Sarawak, Malaysia. Future Energy, 1(2), 28-45, 2022.

[3] "Cambodia - Countries & Regions," IEA, Dec. 06, 2020. https://www.iea.org/countries/cambodia (accessed Dec. 07, 2020).

[4] B. K. Das and F. Zaman, "Performance analysis of a PV/Diesel hybrid system for a remote area in Bangladesh: Effects of dispatch strategies, batteries, and generator selection," energy, vol. 169, pp. 263–276, Feb. 2019, doi: 10.1016/j.energy.2018.12.014.

[5] J. Li, P. Liu, and Z. Li, "Optimal design and techno-economic analysis of a solar-wind-biomass off-grid hybrid power system for remote rural electrification: A case study of west China," Energy, vol. 208, p. 118387, Oct. 2020, doi: 10.1016/j.energy.2020.118387.

[6] C. Li, D. Zhou, H. Wang, H. Cheng, and D. Li, "Feasibility assessment of a hybrid PV/diesel/battery power system for a housing estate in the severe cold zone—A case study of Harbin, China," energy, vol. 185, pp. 671–681, Oct. 2019, doi: 10.1016/j.energy.2019.07.079.

[7] A. Ajlan, C. W. Tan, and A. M. Abdilahi, "Assessment of environmental and economic perspectives for renewable-based hybrid power system in Yemen," Renew. Sustain. Energy Rev., vol. 75, pp. 559–570, Aug. 2017, doi: 10.1016/j.rser.2016.11.024.

[8] M. A. Baseer, A. Alqahtani, and S. Rehman, "Techno-economic design and evaluation of hybrid energy systems for residential communities: Case study of Jubail industrial city," J. Clean. Prod., vol. 237, p. 117806, Nov. 2019, doi: 10.1016/j.jclepro.2019.117806.

[9] O. D. T. Odou, R. Bhandari, and R. Adamou, "Hybrid off-grid renewable power system for sustainable rural electrification in Benin," Renew. Energy, vol. 145, pp. 1266–1279, Jan. 2020, doi: 10.1016/j.renene.2019.06.032.

[10] O. Krishan and S. Suhag, "Techno-economic analysis of a hybrid renewable energy system for an energy poor rural community," J. Energy Storage, vol. 23, pp. 305–319, Jun. 2019, doi: 10.1016/j.est.2019.04.002.

[11] K. Murugaperumal and P. Ajay D Vimal Raj, "Feasibility design and techno-economic analysis of hybrid renewable energy system for rural electrification," Sol. Energy, vol. 188, pp. 1068–1083, Aug. 2019, doi: 10.1016/j.solener.2019.07.008.

[12] M. R. Elkadeem, S. Wang, S. W. Sharshir, and E. G. Atia, "Feasibility analysis and techno-economic design of grid-isolated hybrid renewable energy system for electrification of agriculture and irrigation area: A case study in Dongola, Sudan," Energy Convers. Manag., vol. 196, pp. 1453–1478, Sep. 2019, doi: 10.1016/j.enconman.2019.06.085.

[13] A. C. Duman and Ö. Güler, "Techno-economic analysis of off-grid PV/wind/fuel cell hybrid system combinations with a comparison of regularly and seasonally occupied households," Sustain. Cities Soc., vol. 42, pp. 107–126, Oct. 2018, doi: 10.1016/j.scs.2018.06.029.

[14] M. Haratian, P. Tabibi, M. Sadeghi, B. Vaseghi, and A. Poustdouz, "A renewable energy solution for standalone power generation: A case study of KhshU Site-Iran," Renew. Energy, vol. 125, pp. 926–935, Sep. 2018, doi: 10.1016/j.renene.2018.02.078.

[15] D. Guangqian, K. Bekhrad, P. Azarikhah, and A. Maleki, "A hybrid algorithm based optimization on modeling of grid independent biodiesel-based hybrid solar/wind systems," Renew. Energy, vol. 122, pp. 551–560, Jul. 2018, doi: 10.1016/j.renene.2018.02.021.

[16] L. M. Halabi, S. Mekhilef, L. Olatomiwa, and J. Hazelton, "Performance analysis of hybrid PV/diesel/battery system using HOMER: A case study Sabah, Malaysia," Energy Convers. Manag., vol. 144, pp. 322–339, Jul. 2017, doi: 10.1016/j.enconman.2017.04.070.

[17] M. Hossain, S. Mekhilef, and L. Olatomiwa, "Performance evaluation of a standalone PV-wind-diesel-battery hybrid system feasible for a large resort center in South China Sea, Malaysia," Sustain. Cities Soc., vol. 28, pp. 358–366, Jan. 2017, doi: 10.1016/j.scs.2016.10.008.

[18] M. K. Shahzad, A. Zahid, T. ur Rashid, M. A. Rehan, M. Ali, and M. Ahmad, "Techno-economic feasibility analysis of a solar-biomass off grid system for the electrification of remote rural areas in Pakistan using HOMER software," Renew. Energy, vol. 106, pp. 264–273, Jun. 2017, doi: 10.1016/j.renene.2017.01.033.

[19] A. Yahiaoui, K. Benmansour, and M. Tadjine, "Control, analysis and optimization of hybrid PV-Diesel-Battery systems for isolated rural city in Algeria," Sol. Energy, vol. 137, pp. 1–10, Nov. 2016, doi: 10.1016/j.solener.2016.07.050.

[20] A. Haghighat Mamaghani, S. A. Avella Escandon, B. Najafi, A. Shirazi, and F. Rinaldi, "Techno-economic feasibility of photovoltaic, wind, diesel and hybrid electrification systems for off-grid rural electrification in Colombia," Renew. Energy, vol. 97, pp. 293–305, Nov. 2016, doi: 10.1016/j.renene.2016.05.086.

[21] S. Salehin, M. T. Ferdaous, R. M. Chowdhury, S. S. Shithi, M. S. R. B. Rofi, and M. A. Mohammed, "Assessment of renewable energy systems combining techno-economic optimization with energy scenario analysis," energy, vol. 112, pp. 729–741, Oct. 2016, doi: 10.1016/j.energy.2016.06.110.

[22] Sk. A. Shezan et al., "Performance analysis of an off-grid wind-PV (photovoltaic)-diesel-battery hybrid energy system feasible for remote areas," J. Clean. Prod., vol. 125, pp. 121–132, Jul. 2016, doi: 10.1016/j.jclepro.2016.03.014.

[23] M. L. Kolhe, K. M. I. U. Ranaweera, and A. G. B. S. Gunawardana, "Techno-economic sizing of off-grid hybrid renewable energy system for rural electrification in Sri Lanka," Sustain. Energy Technol. Assess., vol. 11, pp. 53–64, Sep. 2015, doi: 10.1016/j.seta.2015.03.008.

[24] “Peimar_EN_SG310M(FB).pdf.” Accessed: Dec. 07, 2020. [Online]. Available: https://www.peimar.com/datasheet/Peimar_EN_SG310M(FB).pdf.

[25] “Gaia-Wind_133_Datasheet_2014.pdf.” Accessed: Dec. 07, 2020. [Online]. Available: https://www.gaia-wind.com/storage/app/images/downloads/Gaia-Wind_133_Datasheet_2014.pdf.

[26] "How HOMER Creates the Generator Efficiency Curve." https://www.homerenergy.com/products/pro/docs/3.11/how_homer_creates_the_generator_efficiency_curve.html (accessed Dec. 07, 2020).

[27] “2VRE-1600TG_1.pdf.” Accessed: Dec. 07, 2020. [Online]. Available: https://www.harrisbattery.com/sites/default/files/product_pdfs/2VRE-1600TG_1.pdf.

[28] "Welcome to HOMER," Dec. 06, 2020. https://www.homerenergy.com/products/pro/docs/latest/index.html (accessed Dec. 07, 2020).

[29] "Capital Recovery Factor," Dec. 06, 2020. https://www.homerenergy.com/products/pro/docs/latest/capital_recovery_factor.html (accessed Dec. 07, 2020).
[30] "Real Discount Rate," Dec. 06, 2020. https://www.homerenergy.com/products/pro/docs/latest/real_discount_rate.html (accessed Dec. 07, 2020).
[31] "Why Would I Do a Sensitivity Analysis?," Dec. 06, 2020. https://www.homerenergy.com/products/pro/docs/latest/why_would_i_do_a_sensitivity_analysis.html (accessed Dec. 07, 2020).